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# The Effect of Erosion on the Solar Wind Stand-Off Distance at Mercury

JAMES A. SLAVIN AND ROBERT E. HOLZER

*Department of Earth and Space Sciences and The Institute of Geophysics and Planetary Physics University of California, Los Angeles, California 90024*

Recent studies have provided quantitative measurements of the effect of dayside magnetic reconnection on the position of the earth's forward magnetopause. By scaling these terrestrial observations to Mercury, it is predicted that the mean solar wind stand-off distance for average solar wind dynamic pressure conditions will be $0.2$–$0.7R_m$ inward from its 'ground state' position. Furthermore, it is expected that the magnetopause will be eroded and/or compressed to within $0.2R_m$ of Mercury's surface a signficant portion of the time. Empirical formulae derived for the earth's magnetosphere are used to determine both solar wind stand-off distances and solar wind dynamic pressures for the two Mariner 10 encounters with Mercury's magnetosphere. It is found that for the first encounter when the interplanetary magnetic field was often southward and substorm signatures are observed inside the magnetosphere, the mean stand-off distance inferred from the boundary crossings is $1.5R_m$ (for $P_{sw} = 6.0 \times 10^{-8}$ dynes/cm$^2$). At the time of the final encounter, the Mariner 10 magnetometer observed no significant southward component in the IMF and no substorm activity was evident. For this encounter, the mean inferred stand-off distance is $1.9R_m$ consistent with the expected effects of magnetic flux transfer within a terrestrial-type magnetosphere. A dipole moment of $6 \pm 2 \times 10^{22}$ G-cm$^3$ is calculated from the observed bow shock and magnetopause positions. Finally, the importance of magnetic flux transfer in the solar wind-magnetosphere-atmosphere-surface interaction at Mercury is briefly discussed.

## INTRODUCTION

On March 29, 1974, Mariner 10 became the first spacecraft to pass through the magnetosphere of the planet Mercury. Approximately 1 terrestrial or 4 Hermaean years later, on March 16, 1975, the spacecraft repeated the feat by crossing the near tail region of Mercury's magnetosphere a second time. As in previous studies the first encounter will be termed MI and the second, MIII.

While the data collected show unequivocally that Mercury possesses a permanent magnetosphere [*Ness et al.*, 1974], little else can be inferred from this limited data set without recourse to assumptions which will not be tested until additional observations become available. The basic assumption of all previous investigators [e.g., *Ness et al.*, 1974; *Siscoe et al.*, 1975; *Russell*, 1977; *Whang*, 1977; *Jackson and Beard*, 1977; *Ogilvie et al.*, 1977] interpreting the Mercury data has been that the solar wind interaction with Mercury is terrestrial in character.

The present study will also adopt this point of view, but will extend the previous analyses by making quantitative estimates of the effect of magnetic flux transfer between the forward magnetosphere and magnetotail on the position of the magnetopause boundary by employing the results of a similar analysis of the earth's magnetosphere [*Holzer and Slavin*, 1978]. Implicit in this approach are the assumptions that the magnetic field just inside the sunward magnetosphere is due predominantly to an intrinsic dipole moment and the Chapman-Ferraro surface current, and that the contributions of ring currents, neutral sheet currents, and higher order planetary moments are small as is the case for the earth. Under these circumstances the distance from the planet's center to the nose of the magnetopause (i.e., the solar wind stand-off distance, $R_s$) is determined principally by the magnitude of the planetary dipole moment, the solar wind dynamic pressure, and the magnetic flux which has been transferred from the dayside magnetosphere to the tail by the reconnection process.



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## MARINER 10 BOUNDARY CROSSINGS

The positions of the four magnetopause crossings observed in terms of sun-Mercury-satellite angle and distance from the center of the planet are [*Whang*, 1977]: inbound MI ($2.81R_m$, 135°), outbound MI ($2.35R_m$, 101°), inbound MIII ($2.33R_m$, 121°), and outbound MIII ($1.70R_m$, 83°) where an aberration in sms angle due to the orbital motion of the planet has been included. As might be expected for a terrestrial-type magnetosphere the field direction vectors show that the two inbound crossings at sms > 110° found tail-like field lines while the two outbound crossings encountered more dipolar configurations.

It has been well established that the forward terrestrial magnetopause surface (i.e., ses angles ≤ 110°), excluding the cusp region, may be represented in geocentric coordinates as an ellipsoid of revolution

$$R(\theta) = L/(1 + 0.4 \cos \theta) \qquad (1)$$

where $\theta$ is the sun-earth-satellite angle, $L$ is the semi-latus rectum, and 0.4 is the eccentricity [*Holzer and Slavin*, 1978]. With this equation it is possible to calculate the solar wind stand-off distance, $R_s = R(\theta = 0)$, at the time of a given magnetopause encounter $(R, \theta)$. Comparisons between observations during periods of different solar wind pressure can be made by means of the relation $R_s = 1/p_{sw}^{1/6}$ [e.g., *Maezawa*, 1974] which may be used to normalize the crossings to a single pressure. When this is done and only encounters during periods of northward IMF and geomagnetic calm are considered, (1) specifies $R(\theta)$ with a standard deviation in $R$ of 4% [*Holzer and Slavin*, 1978]. The fit to the mean magnetopause position observed by *Fairfield* [1971] is better than 4% for $\theta \le 110°$. It should also be noted that, as shown in Figure 2 of *Fairfield* [1971], an ellipse provides a better fit to the observational data than dissipationless MHD models [e.g., *Olson*, 1969; *Choe et al.*, 1973] except for the forward portions where they agree. Between 60° and 110° the deviation in $R(\theta)$ between *Fairfield*'s [1971] mean magnetopause surface and the various theoretical surfaces grows from ~0 to ~$3R_e$ (R. J. Walker, private communication, 1978). The presently available theoretical models

TABLE 1. Stand-Off Distances From MP Crossings

| MP Crossing | $R_s$ (ellipse) | $R_s$[*Ogilvie et al.*, 1977] |
|---|---|---|
| MI outbound | $1.55R_m \pm 8\%$ | $1.33R_m$ |
| MIII outbound | $1.27R_m \pm 10\%$ | $1.26R_m$ |

become less accurate along the flanks of the magnetosphere due to both a lack of physical knowledge and the nature of the assumptions necessary in order to make the problem numerically tractable. The interested reader is referred to the review articles by *Spreiter* [1975] and *Walker* [1976].

As no accurate method for predicting $R_s$ (i.e., $\Delta R_s/R_s \le 10\%$) from a magnetopause crossing at $\theta > 110°$ has yet been demonstrated, we will not attempt to infer such information from the two inbound Mariner 10 magnetopause crossings. In addition it is not known how $R_s$ determined from crossings at large ses angles varies with different interplanetary conditions to the degree necessary for quantitative comparisons. Shown in Table 1 are the stand-off distances inferred from the two outbound encounters and (1) along with the values of $R_s$ found by *Ogilvie et al.* [1977] using the theoretical model of *Choe et al.* [1973]. As expected from the preceding discussion the two models agree more closely for the MIII encounter than for MI as the former occurred at a smaller sms angle. From (1),

$$R_s = R(1 + \epsilon \cos\theta)/(1 + \epsilon) \tag{2}$$

so that

$$\frac{\Delta R_s}{R_s} = \left|\frac{\Delta R}{R}\right|_{\theta,\epsilon} + \left|\frac{(\epsilon \sin\theta)\Delta\theta}{(1+\epsilon\cos\theta)}\right|_{R,\theta} + \left|\frac{(\cos\theta - 1)\Delta\epsilon}{(1+\epsilon)(1+\epsilon\cos\theta)}\right|_{R,\epsilon} \tag{3}$$

where the magnetopause has been assumed to be an ellipsoid of revolution with $R$, $\theta$, and $\epsilon$, the eccentricity, measured quantities. It is estimated that $\Delta\theta \le 0.03$ rad, $\Delta R \le 0.1R_m$ including the uncertainty in the aberration angle for the two outbound crossings, and $\Delta\epsilon \le 0.03$ from a previous study [*Holzer and Slavin*, 1978]. Using these values in (3) leads to the computation of uncertainties of 8% and 10% in $R_s$ for MI and MIII, respectively.

From studies of terrestrial bow shock crossings it is known that for ses angles less than 130° the shape of this boundary can be modeled as a paraboloid of revolution with one focus at the earth's center

$$R_{ss}^2 = \frac{R^2}{2}\left\{1 - \frac{1}{3}\sin^2\theta \pm \left[\left(1 - \frac{1}{3}\sin^4\theta\right)^2 - \frac{4}{9}\sin^4\theta\right]^{1/2}\right\} \tag{4}$$

where $R_{ss}$ is the distance to the nose of the bow shock and the minus sign is chosen for $90° < \theta < 130°$ [*Campbell*, 1976]. Because the position of the shock is determined by the forward position of the obstacle we can make use of all four shock encounters to infer solar wind stand-off distances. In calculating the distance to the nose of the magnetopause from the nose position of the shock the relationship $R_{ss} = 1.33R_s$ for high mach shocks was assumed [*Fairfield*, 1971]. Table 2 lists the solar wind stand-off distance for each of the four encounters based upon the mean observed position of the boundaries. Previously, *Russell* [1977] has inferred values of $R_s$ for these crossings using an ellipse to model the bow shock. While he did not publish the individual values for each encounter, Russell's published mean of $1.4 \pm 0.1R_m$ is in good agreement with our results as indicated in the table. A standard error analysis on (4) shows that for the range in sms angle considered here,

$$\frac{\Delta R_s}{R_s} \le \left|\frac{\Delta R}{R}\right|_{\theta} + \left|\Delta\theta\right|_{R} \tag{5}$$

For multiple bow shock crossings the mean position has been used for $R$ and $\theta$ in (4) and (5) with $\Delta R$ and $\Delta\theta$ determined by the change in position from the first to the last encounter.

## SOLAR WIND DYNAMIC PRESSURE

Studies at the earth have found that a knowledge of the magnetic flux density just inside the dayside magnetopause is a good indicator of solar wind pressure. *Maezawa* [1974] has shown on the basis of Ogo 5 observations that the field along the dayside magnetopause varies as $B_0/R^3$ for a given solar wind pressure. Thus, the observed magnetic field magnitude just inside the magnetopause can be used to infer the flux density at the nose of the magnetopause. For the MI outbound pass, this method yields a value of 170 $\gamma$ for the field strength at the stagnation point, $B_s$, and for MIII outbound a value of 240 $\gamma$. These values of $B_s$ at the subsolar point imply solar wind dynamic pressures of $P_{sw} = (B_s^2/8\pi)/0.88 = 1.3 \times 10^{-7}$ dynes/cm$^2$ and $2.6 \times 10^{-7}$ dynes/cm$^2$ for MI and MIII, respectively. When this method is applied to the earth, it agrees with the plasma observations made by near-earth orbiting satellites to within 10% [*Holzer and Slavin*, 1978]. As the uncertainty in the magnetic flux density just inside the magnetopause is 10% or less as determined by examining the Mariner 10 data, the uncertainty in solar wind dynamic pressure is approximately 30% as indicated in Table 5. The interaction constant of 0.88 is believed to be well determined from both the theoretical models and experimental observations [*Spreiter*, 1975; *Holzer and Slavin*, 1978].

While only the magnetic field observations made near the outbound magnetopause crossings can be used to determine $P_{sw}$ by the above method, similar results can be derived from the Mercury magnetic observations as a whole as shown by *Jackson and Beard* [1977]. In that study, the terrestrial magnetosphere was scaled to fit the Mercury observations with the ratio of the magnetic field magnitude at the nose of the Hermaean magnetopause to the mean magnitude at that position in the terrestrial magnetosphere as one of the free parameters to be determined. *Jackson and Beard* [1977] found this ratio to be 2.21 for the first half of MI and 4.28 for all of MIII when the Hermaean magnetic field was assumed dipolar. For a mean stagnation field at the earth of 60$\gamma$ it is found that $B_s = 133\ \gamma$ for the first half of MI and 257$\gamma$ for all of MIII so that $p_{sw} = 8.0 \times 10^{-8}$ dynes/cm$^2$ and $p_{sw} = 3.0 \times 10^{-7}$ dynes/cm$^2$, respectively. In using these pressures, we will assume that the uncer-

TABLE 2. Solar Wind Stand-Off Distances From BS Crossings

| Bow Shock Crossing | $R_s$ |
|---|---|
| MI | |
| Inbound | $1.17R_m \pm 9\%$ |
| Outbound | $1.26R_m \pm 15\%$ |
| MIII | |
| Inbound | $1.63R_m \pm 6\%$ |
| Outbound | $1.55R_m \pm 12\%$ |
| Mean | $1.40R_m \pm 10\%$ |
| Mean [*Russell*, 1977] | $1.40R_m \pm 7\%$ |

TABLE 3. SW Parameters From Mariner 10 Electron Observations

| Pass | Velocity, km/s | Density, $cm^{-3}$ |
|---|---|---|
| MI | | |
| Inbound | 550 ± 50 | 14 ± 3 |
| Outbound | 550 ± 50 | 14 ± 3 |
| MIII inbound | 600 ± 50 | 10 ± 4 |

tainty to be no greater than was inferred for the previous method or 30% as displayed in Table 5.

Another source of solar wind data during the Mariner 10 Mercury encounters were the in situ observations made by the electron plasma experiment [e.g., *Ogilvie et al.*, 1977]. This instrument measured the electron flux at 15 energies between 13 and 715 eV with an energy spectrum compiled every 6 s. It was mounted on a scan platform facing away from the sun. While the preliminary determination of the dynamic pressure with this instrument for MI was $1.1 \times 10^{-7} \pm 10\%$ dynes/cm$^2$ [*Ogilvie et al.*, 1974], the final results after corrections for spacecraft charging effects are shown in Tables 3 and 5 (K. W. Ogilvie, private communication, 1978). For the inbound portion of MI the error bars on $p_{sw}$ inferred from the electron data and the magnetic field model of *Jackson and Beard* [1977] overlap. Similarly, for MI outbound the values of $p_{sw}$ arrived at with the electron observations and the magnetic field magnitude just inside the outbound magnetopause may be reconciled by oppositely directed errors. However, in all cases the electron observations suggest a lower solar wind pressure than that inferred from the magnetometer data.

In an effort to gain some additional information concerning the solar wind dynamic pressure during MI and MIII we have traced the solar wind plasma at Mercury back to the longitude on the sun from whence it originated under the assumption of a solar wind velocity of 650 ± 50 km/s. It is then possible with a knowledge of the sun's rotation rate to calculate when plasma originating from that same longitude reached the earth. The earth-based observations [*King*, 1977] indicate that during both of the Mariner 10 Mercury encounters the planet was interacting with the enchanced velocity portion of a recurrent high speed stream. The stream structure of the solar wind at the time of MI has been analyzed by *Behannon* [1976] and is consistent with this finding. By assuming solar wind velocity to be independent of radial distance from the sun and number density $\propto r^{-2}$ the solar wind conditions during MI and MIII may be inferred as shown in Table 4. While this method cannot claim high precision, the comparison between Tables 3 and 4 is acceptable except for the density during MIII.

The values of $p_{sw}$ derived by the four methods discussed are summarized in Table 5. In this study, the pressures inferred from the outbound magnetopause magnetic observations will be used and assumed valid for the full extent of each encounter. From Table 5 it is seen that these values with the stated uncertainties are in fair agreement with the pressures inferred by other means save the Mariner 10 electron observations for MIII. In Table 6 the values of $R_s$ determined earlier have been scaled to a common dynamic pressure of $6.0 \times 10^{-8}$ dynes/cm$^2$ which is near the expected mean dynamic pressure at 0.47 AU [*Siscoe and Christopher*, 1975]. As shown, the stand-off distances vary from 1.3 to 2.1$R_m$ with the means for MI and MIII being 1.5 and 1.9$R_m$, respectively. Hence, the variation in stand-off distance from one boundary encounter to the next is much larger than the 0.2–0.3$R_m$ uncertainty in the inferred values of $R_s$.

## EFFECT OF FLUX TRANSFER ON MAGNETOPAUSE POSITION

*Siscoe et al.* [1975] have considered substorms as a possible source of the large amplitude fluctuations in both the magnetic field and electron flux measurements observed during the outbound leg of MI. In that analysis, it was shown that the magnetosphere of Mercury appears to be similar to a terrestrial magnetosphere scaled down by the ratio of the solar wind stand-off distances in planetary radii. For the earth's magnetosphere the time span of substorm related phenomena is given approximately by the time necessary for tail plasma to $\mathbf{E} \times \mathbf{B}$ drift one tail radius [*Siscoe et al.*, 1975], ~2.5 hr for a convection potential for 55 kV corresponding to $Kp = 4.5$ [*Kivelson*, 1976]. For Mercury, the convection time for a cross-tail potential of 13 kV [*Hill et al.*, 1976] is ~6 min. This time scale is of importance in considering the Mariner 10 observations because the satellite spent only ~15 min inside the Hermaean magnetosphere during each encounter. The individual bow shock and magnetopause encounters were separated temporally by about 1–3 times the calculated convection time. Hence, the observed positions of these boundaries may reflect different states of this magnetosphere with respect to the changes in configuration associated with magnetic flux transfer and substorms as is suggested by the observed variation in $R_s$.

One approach to modeling the effects of dayside magnetic merging between the interplanetary and geomagnetic fields is to use the concept of a reconnection, or erosion, efficiency introduced by *Levy et al.* [1964] and subsequently used to interpret magnetospheric data by *Burch* [1973] and *Slavin and Holzer* [1977]. The magnetic flux eroded, $\delta\Phi_e$, in a given period of time and transferred to the magnetotail is given by

$$\delta\Phi_e = \alpha\Phi_{ap} = \alpha \int 2.8R_s V_{sw} B_z^- \, dt \qquad (6)$$

where $\Phi_{ap}$ is the applied flux of southward IMF field lines, $\alpha$ is the erosion efficiency, $2.8R_s$ is the width of the dayside magnetosphere, and $B_z^-$ is the magnitude of the negative $z$ component of the IMF in GSM coordinates. For the earth's magnetosphere a value of 0.2 for $\alpha$ has been inferred from observing contractions of the dayside magnetopshere in response to a southward IMF [*Slavin and Holzer*, 1977]. However, in applying these concepts to the Hermaean magnetosphere it must be noted that in the hydromagnetic merging models the erosion efficiency is proportional the Alfvén velocity in the magnetosheath with respect to the $B_z^-$ component of the magnetosheath magnetic field [e.g., *Sonnerup*, 1974]. This quantity is then proportional to $B_z^-/(4\pi\rho)^{1/2}$ in the solar wind. *Behannon* [1978] has reported that the magnitude of the theta component of the IMF varies as $r^{-(1.4\pm0.6)}$ between 1 and 0.46 AU where the empirical uncertainties allow values from about $r^{-1}$ to $r^{-2}$. Since solar wind density varies as $r^{-2}$, it is apparent that if $B_z^- \propto r^{-1}$, the hydromagnetic erosion efficiencies for the earth and Mercury would be approximately equal. However, if $B_z^- \propto r^{-2}$, then it might be expected that the erosion efficiencies for a terrestrial-type magnetosphere will vary as $r^{-1}$ for $r \lesssim 1$ AU.

Among the observed effects of erosion are contractions and expansions of the dayside magnetopause [*Aubry et al.*, 1970; *Holzer and Slavin*, 1978] as a result of magnetic flux transfer.

TABLE 4. Earth SW Observations Scaled to 0.46 AU

| Encounter | Velocity, km/s | Density, $cm^{-3}$ |
|---|---|---|
| MI | 650 | 20 |
| MIII | 630 | 30 |

TABLE 5. Summary of $P_{sw}$ Determinations

| Pass | $P_{sw}(B_s)$ | $P_{sw}(e^-$ Obs.) | $P_{sw}$ [*Jackson and Beard*] | $P_{sw}$ (Earth Obs.) |
|---|---|---|---|---|
| MI | | | | |
| Inbound | | $6.8 \pm 3 \times 10^{-8}$ | $8.0 \times 10^{-8} \pm 30\%$ | $\sim 1 \times 10^{-7}$ |
| Outbound | $1.3 \times 10^{-7} \pm 30\%$ | $6.8 \pm 3 \times 10^{-8}$ | | $\sim 1 \times 10^{-7}$ |
| MIII | | | | |
| Inbound | | $5.8 \pm 4 \times 10^{-8}$ | $3.0 \times 10^{-7} \pm 30\%$ | $\sim 2 \times 10^{-7}$ |
| Outbound | $2.6 \times 10^{-7} \pm 30\%$ | | $3.0 \times 10^{-7} \pm 30\%$ | $\sim 2 \times 10^{-7}$ |

These contractions and expansions, independent of any compressions and rarefactions resulting from changes in solar wind dynamic pressure, occur because of the time lag of ~40 min between the southward turning of the IMF and the establishment of an equilibrium in which the rate of magnetic flux erosion equals the rate of flux return [e.g., *Arnoldy*, 1971; *Rostoker et al.*, 1972; *Coroniti and Kennel*, 1973; *Holzer and Reid*, 1975]. The principal cause of this time lag is believed to be line-tying effects in the earth's ionosphere. Hence, during the first 40 min following a southward turning of the IMF the net flux transferred to the tail, $\Delta\Phi = |\delta\Phi_e - \delta\Phi_r|$, the difference between the amount of flux eroded and returned becomes just $\Delta\Phi \simeq \delta\Phi_e$. This net transfer of flux to the tail will result in a contraction of the dayside magnetosphere observed as an inward displacement of the magnetopause. For the terrestrial magnetosphere the average net flux transferred to the geomagnetic tail during an erosion event may be estimated from (6) as $\Delta\Phi = 0.2(40 \times 60$ s) $(2.8 \times 11 \times 6380 \times 10^5$ cm) (400 km/s) ($2\gamma$) $= 7.5 \times 10^{15}$ Maxwells, which is in good agreement with observation [*Holzer and Slavin*, 1978]. Because Mercury lacks an ionosphere, the time delays due to line-tying effects may not be as important as they are for the earth. However, the response time of the Hermaean magnetosphere, $T_{rm}$, to the IMF becoming southward cannot be less than the time necessary for the solar wind to 'pull' the flux back into the tail. Therefore, the minimum response time may be estimated as

$$T_{rm} \gtrsim \frac{2L}{V_{sw}} \simeq \frac{20R_m}{400 \text{ km/s}} \simeq 2 \text{ min} \tag{7}$$

where $L$ is the distance to the region of the tail in which reconnection might be expected to occur. MI provides additional information concerning the magnitude of $T_{rm}$. The interplanetary magnetic field was oriented primarily southward until 4 min prior to the spacecraft's encounter with Mercury's bow shock. During this interval of extended erosion it is expected that an equilibrium would have been established between the rates at which magnetic flux is transferred to and from the tail with the magnetopause displaced in toward the planet's surface. After the IMF turns northward magnetic flux will continue to be returned from the tail for a period of time on the order of $T_{rm}$ at the end of which the magnetopause will have expanded out to its uneroded or 'ground state' position. The value of $R_s$ inferred from the inbound bow shock is the smallest observed, $1.3R_m$ for $p_{sw} = 6 \times 10^{-8}$ dynes/cm², indicating that $T_{rm} > 4$ min as $R_s$ has not yet reached its uneroded value of approximately $2.1R_m$, the largest value of $R_s$ observed. Upon penetrating into the magnetosphere 14 min after the IMF turned northward the magnetic field is relatively steady and does not exhibit evidence of enhanced and/or time varying neutral sheet current as is seen during the outbound portion of MI during which the IMF is believed to have turned southward again resulting in magnetic flux transfer and substorm activity [*Siscoe et al.*, 1975]. This observation suggests that $T_{rm} < 14$ min so that our best estimate of the response time from the Mariner 10 data is

$$4 \text{ min} < T_{rm} < 14 \text{ min} \tag{8}$$

The importance of erosion in determining $R_s$ at the earth can be seen in Figure 1 from the study by *Holzer and Slavin* [1978] which plots $P(R_c)$, the probability of observing $R_s \leq R_c$, where $R_c$ is distance in units of $11R_e$, versus $R_c$ for $p_{sw} = 1.44 \times 10^{-8}$ dynes/cm² at 1 AU. For example, there is a 50% chance of $R_c \leq 0.94$ (i.e., $R_s \leq 10.3R_e$) due to the effects of erosion while the uneroded stand-off distance for that value of $p_{sw}$ is $11.0R_e$. The failure of the curve to reach 100% at $R_c = 1$, the uneroded stand-off distance, is attributed to the effects of ring current and other experimental uncertainties.

Thus, because of the importance of magnetic flux transfer in determining the terrestrial magnetopause position, it is of interest to apply these results to the Hermaean magnetosphere in order to properly interpret the stand-off distances inferred from the Mariner 10 data. The net amount of flux eroded from the dayside magnetosphere is determined by solar wind parameters and $T_{rm}$ so that

$$\Delta\Phi \propto \alpha R_s B_z^- V_{sw} T_{rm} \tag{9}$$

This net transfer of flux may be related to an inward displacement of the standoff distance, $\Delta R_s$, by

$$\Delta\Phi \propto B_s R_s \Delta R_s \tag{10}$$

where $B_s$ is the magnitude of the total magnetic field just inside the nose of the magnetopause. Combining these two relations yields

$$\Delta R_s \propto \alpha B_z^- V_{sw} T_{rm} / B_s \tag{11}$$

By assuming $V_{sw}$ and $\alpha$ independent of heliocentric distance, $B_z^- \propto r^{-1}$, and $B_s \propto (P_{sw})^{1/2} \propto r^{-1}$, $\Delta R_s$ is directly proportional to $T_{rm}$ alone. Thus, it is the response time that is the critical parameter in determining the effect of erosion on the internal distribution of magnetic flux. However, if $B_z^- \propto r^{-2}$, then $\alpha \propto r^{-1}$, so that $\Delta R_s \propto T_{rm}\, r^{-2}$ in which case the inward displacements due to erosion depend upon heliocentric distance as well as the response time.

TABLE 6. $R_s$ Values Scaled to $P_{sw} = 6.0 \times 10^{-8}$ Dynes/cm²

| Crossing | $R_s$ |
|---|---|
| MI | |
| Inbound BS | $1.33R_m \pm 14\%$ |
| Outbound MP | $1.76R_m \pm 13\%$ |
| Outbound BS | $1.43R_m \pm 20\%$ |
| MIII | |
| Inbound BS | $2.08R_m \pm 11\%$ |
| Outbound MP | $1.62R_m \pm 15\%$ |
| Outbound BS | $1.98R_m \pm 17\%$ |

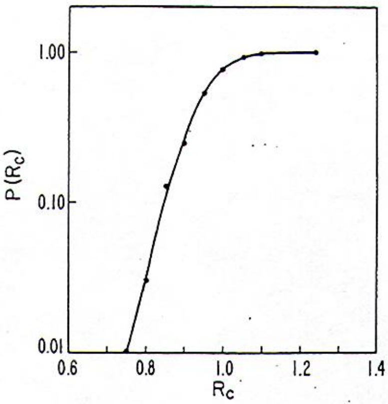


Fig. 1. $P(R_c)$, the probability of observing the magnetopause along the sun-earth line at a distance $R = 11R_eR_c$ or less, plotted against $R_c$ for 87 Ogo 5 magnetopause encounters in 1968–1969 which have been scaled to a mean solar wind pressure of $1.44 \times 10^{-8}$ dynes/cm² [from *Holzer and Slavin,* 1978].

From Figure 1, it is seen that 50% of the time the terrestrial magnetopause subsolar distance is displaced inward by $0.7R_e = 4.5 \times 10^3$ km. With (8) and (11) and an assumed radial dependence of $r^{-1}$ for $B_z^-$ it is possible to estimate the distance by which the Hermaean magnetopause is expected to be displaced inward from the uneroded position 50% of the time, $\langle \Delta R_{sm} \rangle$. Thus,

$$\langle \Delta R_{sm} \rangle = \frac{T_{rm}}{T_{re}} \langle \Delta R_{se} \rangle \qquad (12)$$

where $\langle \Delta R_{se} \rangle$ is the mean inward displacement at the earth, $\langle \Delta R_{sm} \rangle$ the mean inward displacement at Mercury, $T_{re}$ is the terrestrial response time, and $T_{rm}$ is the response time of Mercury's magnetosphere. Hence for $\langle \Delta R_{se} \rangle = 4.5 \times 10^3$ km, $T_{re} = 40$ min, and (8) we find that

$$4.5 \times 10^2 \text{ km} \leq \langle \Delta R_{sm} \rangle \leq 1.6 \times 10^3 \text{ km}$$

or

$$0.2R_m \leq \langle \Delta R_{sm} \rangle \leq 0.7R_m \qquad (13)$$

While the uncertainty in $T_{rm}$ and $B_z^-(0.31 \text{ AU} < r < 0.47 \text{ AU}, t)$ is not small, (13) demonstrates that the size of dayside magnetosphere at Mercury may be quite variable as indicated by Mariner 10 observations in Table 6 where the difference between the maximum and minimum values of $R_s$ is $0.8R_m$. Figure 2 plots $\langle \Delta R_{sm} \rangle$ as a function of $T_{rm}$ over the domain of expected values for the response time. It must be noted that if it were assumed that $B_z^- \propto r^{-2}$ larger inward displacements that are shown in (13) by a factor of $(0.47)^{-2}$ to $(0.31)^{-2}$ or 4.5 to 10.4 depending on Mercury's distance from the sun would be found. In addition, the use of (12) to scale the terrestrial findings of *Holzer and Slavin* [1978] underestimates the effects of erosion at Mercury in that the coefficient $(T_{rm}/T_{re})$ is correct only for periods of southward IMF lasting 40 min or longer. For southward intervals less than $T_{rm}$ the coefficient should be unity and for intervals of length $t$ such that $T_{rm} < t < T_{re}$ this coefficient should be $(T_{rm}/t)$. As $1 > (T_{rm}/t) > (T_{rm}/T_{re})$ the use of (12) in arriving at (13) underestimates the magnitude of the inward displacements at Mercury, but avoids the need for making additional assumptions concerning the temporal variation in southward orientations of the IMF with radial distance from the sun.

## UNERODED SOLAR WIND STAND-OFF DISTANCE AND THE PLANETARY DIPOLE MOMENT

Observationally, there are two methods that may be used to determine the solar wind stand-off distance for a terrestrial-type magnetosphere in the absence of any net magnetic flux transfer from the dayside magnetosphere. By using satellite observations of the IMF in conjunction with data from other satellites within the planetary magnetosphere and, if the planet possess a significant ionopshere, ground based auroral zone magnetometers, the position of the magnetopause may be examined directly during periods of time when the IMF is oriented antiparallel to the planetary dipole and magnetospheric activity is low in order to determine the uneroded solar wind stand-off distance as a function of solar wind dynamic pressure. The other approach is to consider all magnetopause encounters for which solar wind dynamic pressure data are available and plot them in the form of a distribution function after scaling to a single value of $p_{sw}$ as was done in Figure 1. The uneroded stand-off distance will correspond approximately to the maximum observed value of $R_s$ for which $P(R_c)$ approaches 100%. Hence, in the absence of significant internal currents, such as the terrestrial 'ring' current, that inflate the dayside magnetosphere, all observed values of $R_s$ will be less than or equal to the uneroded stand-off distance. There was no magnetic evidence for such internal currents observed during either MI or MIII.

As there were no other satellites near Mercury to monitor the IMF, the latter method must be used to estimate the uneroded solar wind stand-off distance. The estimated uneroded stand-off distance for $p_{sw} = 6.0 \times 10^{-8}$ dynes/cm² is then $\sim 2.1R_m$, the maximum observed value of $R_s$ as shown in Table 6. Hence, the best estimate of the uneroded nose position for $p_{sw} = 6.0 \times 10^{-8}$ dynes/cm² possible with these data is $2.1 \pm 0.2R_m$ for uncertainties in $p_{sw}$ and $R_s$ of 30% and 6%, respectively, as shown in the tables.

Determination of Mercury's magnetic moment by fitting the Mariner 10 magnetic field observations is made difficult by both the paucity of data and relatively large contributions to the observed field by the magnetopause and internal currents. Different treatments of this data analysis problem have yielded value of $M_0$ from $5.2 \times 10^{22}$ G-cm³ to $2.4 \times 10^{22}$ G-cm³ [*Ness et al.,* 1976; *Whang,* 1977; *Jackson and Beard,* 1977; *Ng and Beard,* 1978]. A good estimate of the terrestrial magnetic moment can be made from a knowledge of the uneroded solar wind stand-off distance. This distance for a solar wind dy-

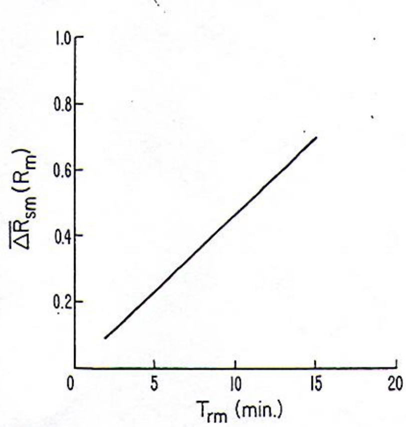


Fig. 2. $\langle \Delta R_{sm} \rangle$, the mean inward displacement from the uneroded solar wind stand-off distance for average solar wind pressure conditions, as a function of the response time over the domain of expected values of $T_{rm}$.

TABLE 7. Probability of $R_s \leq 1.2R_m$

| Position | Prob ($R_s \leq 1.2R_m$) |
|---|---|
| Aphelion | 0.03 for $B_z^- \propto r^{-1}$ |
| | 0.15 for $B_z^- \propto r^{-2}$ |
| Perihelion | 0.06 for $B_z^- \propto r^{-1}$ |
| | 0.60 for $B_z^- \propto r^{-2}$ |

namic pressure of $1.44 \times 10^{-8}$ dynes/cm² is $11.0 \pm 0.4R_e$ [*Holzer and Slavin,* 1978]. Using theoretical values for the $f$ and $k$ coefficients of the solar wind-magnetosphere interaction [e.g., *Spreiter,* 1975], we may write

$$M_0 = (2\pi\rho v^2 R_s{}^6 k/f^2)^{1/2} \tag{14}$$

where $f = 1.22$ and $k = 0.88$. For the earth, this yields $M_0 = 8.0 \times 10^{25}$ G-cm³ in excellent agreement with the actual moment as determined from ground measurements. However, Figure 1 indicates that if a probe were to encounter the terrestrial magnetopause a number of times at a solar wind dynamic pressure of $1.44 \times 10^{-8}$ dynes/cm² a 'mean' stand-off distance of $10.3R_e$ would be observed. When this mean value of $R_s$ is used the magnetic moment inferred for the earth is $6.6 \times 10^{22}$ G-cm³, an underestimate of 20%. It is the uneroded, and not the mean, stand-off distance which should be used in determining planetary magnetic dipole moments with (14) and these theoretical values of $f$ and $k$ which were calculated for a ground state terrestrial magnetosphere. If the uneroded value of $R_s$ at Mercury is in fact $2.1R_m$ for $P_{sw} = 6.0 \times 10^{-8}$ dynes/cm² as is suggested in this paper, then a value of $M_0 = 6 \pm 2 \times 10^{22}$ G-cm³ is obtained from (14). This finding is in substantial agreement with the dipole moments inferred by *Ness et al.* [1976] from modeling the Mariner 10 magnetometer data with the intrinsic centered dipole moment and an assumed uniform perturbation field due to the magnetospheric currents. The stand-off distances and solar wind pressures calculated in this study are not consistent with the intrinsic dipole, quadrupole, and octupole moments found by *Whang* [1977], *Jackson and Beard* [1977], and *Ng and Beard* [1978] using more elaborate models of the magnetospheric currents, but attributing the observed field to non-dipole moments or dipole offsets as well as centered dipole moments. However, a final determination of the Hermaean magnetic moment will not be possible until an orbiter mission is completed.

## VARIATION IN SOLAR WIND STAND-OFF DISTANCE

*Siscoe and Christopher* [1975] have studied the variations in solar wind stand-off distance at Mercury using solar wind data collected at 1 AU. In that paper, it was assumed that Mercury possessed a dipole moment of $5.1 \times 10^{22}$ G-cm³ and responded to changes in the solar wind pressure in the same way as the terrestrial magnetosphere. The effects of merging were not included in the calculations. Solar wind dynamic pressure at earth orbit was scaled to that of Mercury's orbit by assuming that the velocity was independent of $r$ while the density varies as $r^{-2}$. In this way, Siscoe and Christopher predicted mean stand-off distances of 2.0 and $1.7R_m$ at aphelion (0.469 AU) and perihelion (0.309 AU), respectively. At both Mercury's closest and farthest approaches to the sun, they found that the magnetopause would be expected to be found within $0.2R_m$ of the planet's surface less than 1% of the time.

It will be assumed that the distribution of $R_s$ due to variations in $p_{sw}$ found by *Siscoe and Christopher* [1975] may be approximated by normal distributions with standard deviations of $0.2R_m$ and means of $1.7R_m$ and $2.0R_m$ for perihelion and aphelion, respectively. In addition, each mean will be multiplied by $(6 \times 10^{22}/5.1 \times 10^{22})^{1/3}$ to scale the planetary dipole moment from the $5.1 \times 10^{22}$ G-cm³ assumed by Siscoe and Christopher to the $6 \times 10^{22}$ G-cm³ suggested in this paper. Hence, the probability of finding a stand-off distance within $dR_s$ of $R_s$ at aphelion in the absence of dayside erosion is

$$P(R_s)\,dR_s = (1/0.08\pi)^{1/2} \exp\left[-(R_s - 2.1)^2/0.08\right] dR_s \tag{15}$$

where all lengths are in $R_m$. The probability of finding the magnetopause within $0.2R_m$ of the planet's surface is then

$$\text{Prob}\,(R_s \leq 1.2R_m) = \int_0^\infty P_e(R_s)P(R_s)\,dR_s \tag{16}$$

where $P(R_s)$ is defined in (15) and $P_e(R_s)$ is the probability of the magnetopause being displaced inward by erosion from $R_s$ by the distance, $R_s - 1.2R_m$. The probability of such an inward displacement can be crudely estimated from Figure 1 as scaled to the Hermaean magnetosphere by (12). In order to obtain a conservative estimate we shall assume $T_{rm} = 2$ min, the solar wind travel time which is half the lower limit on the response time suggested by our interpretation of the MI observations. When the integration described in (16) is performed in this mannner, it is found that the magnetopause should be eroded and/or compressed to within $0.2R_m$ of Mercury's surface 6% of the time at perihelion and 3% at aphelion. In addition, it must be noted that if $B_z^- \propto r^{-2}$, the effect of erosion on the stand-off distance increases both because of an increase in the erosion efficiency and $\Phi_{ap}$ as the distance from the sun decreases. For this radial variation in $B_z^-$ the stand-off distance will be less than $1.2R_m$ approximately 60% of the time at perihelion and 15% of the time at aphelion. These findings are summarized in Table 7. As (12) and therefore (16) are linear in $T_{rm}$, the predicted probabilities for a response time of 4 or 6 min can be obtained by multiplying the results listed in Table 7 by 2 or 3, respectively. The main conclusion to be drawn from these calculations is that Mercury may in fact frequently possess little or no dayside magnetosphere.

## DISCUSSION

In the preceding analysis, a simple model of magnetic flux transfer in the terrestrial magnetosphere has been applied to the magnetosphere of Mercury. It is found that the magnitude of the inward displacements of the dayside magnetopause associated with the net transfer of flux within the magnetosphere is proportional to the magnetospheric response time. While it is not possible to determine this time constant with a high degree of certainty from the Mariner 10 observations, $T_{rm}$ is not expected to be less than 1 or 2 min and the inbound MI observations suggest a value between 4 and 14 min. The calculations presented in this paper find that for $T_{rm} \gtrsim 1$ min magnetic flux transfer will be a significant consideration in determining the configuration of the Hermaean magnetosphere. In particular, the results displayed in Table 7 show that the dayside magnetosphere of this planet may be frequently eroded inward to the point where direct interaction between the solar wind and the planetary surface becomes possible. No attempt to model this interaction has been made in this study, but inductive effects may contribute significantly [*Hood and Schubert,* 1979].

An examination of the Mariner 10 encounters with the Hermaean bow shock and magnetopause found that the solar wind stand-off distance, scaled to $p_{sw} = 6.0 \times 10^{-8}$ dynes/cm², ranged from 1.3 to $2.1R_m$. This variation in $R_s$ is consistent with the expected effects of magnetic flux transfer. In addition, these boundaries were found closer to the planet's surface for MI, $\langle R_s \rangle = 1.5R_m$, during which southward IMF and substorm signatures were observed than for MIII, $\langle R_s \rangle = 1.9R_m$, when the IMF was predominantly northward and no substorm activity was evident. These findings are consistent with the observed behavior of the terrestrial magnetosphere [e.g., *Meng,* 1970; *Fairfield,* 1971].

The large variation in the size of Mercury's dayside magnetosphere predicted by this study is also of planetological and atmospheric interest. For example, the probability of surface saturation by solar wind ions is enhanced by the values in Table 7, while the time averaged magnetospheric cross section that may absorb solar wind constituents which contribute to the Hermaean exosphere is reduced [e.g., *Kumar,* 1976; *Curtis and Hartle,* 1978, and references therein]. In addition, a more precise determination of $T_{rm}$ and/or the observation of inductive effects on $R_s$ by an orbiter mission may provide information concerning the electrical conductivity near the planet's surface. Consequently, in future studies of the solar wind-magnetosphere-atmosphere-surface interactions at Mercury the effects of magnetic flux transfer may be of importance.

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